NAVAL POSTGRADUATE SCHOOL
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THESIS

AN EXPERIMENTAL INVESTIGATION OF THE COMBUSTION BEHAVIOR OF SOLID FUEL RAMJETS

by

Grant Allan Begley, Jr.

December 1982

Thesis Advisor: D. W. Netzer

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An Experimental Investigation of the Combustion Behavior of Solid Fuel Ramjets

by

Grant Allan Begley, Jr.
Lieutenant, United States Navy
B.S., United States Naval Academy, 1975

Submitted in partial fulfillment of the requirements for the degree of

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ABSTRACT

Limited experimental data indicated that fuel vapor composition within the SFRJ combustor may have a significant effect on the obtainable combustion efficiency and upon the dependence of combustion efficiency upon equivalence ratio and air mass flow rate. Combustor pressure oscillations in bypass operation were found to increase regression rates when using PMM fuel grains and to increase or decrease combustion efficiency depending upon equivalence ratio.

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LIST OF SYMBOLS

A	area
A^*	nozzle throat area
f/a	fuel-air ratio
d	orifice diameter
D	diameter (pipe, fuel grain)
L	PMM fuel grain length
$\dot{m}$	mass flow rate
P	pressure
R	gas constant
$\dot{r}$	fuel regression rate
t_b	burn time
T	temperature
T_{ex}	experimental combustion stagnation temperature
T_{th}	theoretical combustion stagnation temperature
Δw_f	weight change of fuel grain
γ	ratio of specific heats
η	temperature rise combustion efficiency
ρ	density
ϕ	equivalence ratio = $\frac{(f/a)}{(f/a)_{\text{stoichiometric}}}$

LIST OF SUBSCRIPTS

a	air, ambient conditions
av	average
c	chamber
f	final, fuel
i	initial
p	propellant
Bp	bypass
t	total (fuel + air)

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I. INTRODUCTION

History informs us that complexity, cost, and performance of weapons and weapon systems are on a constant increase. Aircraft carriers costing 2 billion dollars and combat aircraft costing 40 million dollars are no longer unusual, or is it unusual for operating speeds of our airborne weapons and platforms to push through Mach 2 and towards the Mach 3 region. Through the increasing demands placed on tactical missiles and joint improvements in warhead and guidance capabilities there has been renewed interest in one of the simplest of all air-breathing engines, the solid fuel ramjet (SFRJ).

The distinguishing features of the solid fuel ramjet are the absence of fuel tankage, fuel delivery, and fuel control systems. The fuel is packaged entirely in the combustor, contributing towards simplicity and reduced cost. The SFRJ combines the simplicity and loading efficiency of a solid propellant rocket motor and the performance of an air-breathing engine.

In order to compete with other modern propulsion systems the SFRJ must demonstrate a reliable and efficient combustion process within the expected operational envelope of altitudes and Mach numbers. Although the SFRJ can operate at subsonic flight speeds, increased diffuser performance accompanying higher flight speeds renders the ramjet most suitable for supersonic flight.

Investigations into the combustion process of the SFRJ have progressed steadily since 1973 at the Naval Postgraduate School. In 1981 Binn, et al [Ref. 1] attempted to relate the reacting and non-reacting flow characteristics of the SFRJ. It was found that an increase in the near-wall turbulence intensity measured in non-reacting flow correlated with an increased fuel grain regression rate in the reacting environment. This in turn can effect the combustion efficiency, depending upon the value of the equivalence ratio. Also in 1981 Metochianakis, et al [Ref. 2] attempted to control combustion efficiency by altering the near-wall turbulence/mixing. It was found that when Plexiglas (PMM) was used as the fuel, combustion efficiency did not vary appreciably with equivalence ratio in non-bypass configurations and that near-wall mixing increased regression rate, but did not increase efficiency. It was also found that 50/50 bypass operation adversely affected the combustion efficiency when PMM fuel grains were tested at equivalence ratios greater than 0.8. However, the lower performance occurred only when combustion pressure oscillations were present. The pressure oscillations increased the fuel regression rate and, therefore, increased the equivalence ratio for the same air flow rates and PMM fuel grain lengths. Thus, it was not clear from the data whether the decreased performance was a result of the combustion pressure oscillations or the increased equivalence ratio.

When HTPB was used as the fuel it was found that combustion efficiency decreased with increased equivalence ratio for non-bypass operation and that the combustion efficiency was much less than that obtained with PMM. However, several significant differences existed in

the test conditions for the two fuel types, primarily because of conditions required to obtain substained combustion. The PMM tests were conducted at low (typically 0.09 kg/sec) flow rates to limit the grain inlet Mach number. This fuel requires a large inlet (sudden-expansion) area ratio (A_{port}/A_{inlet}) to provide flame stability. For simplicity the tests were also conducted using room temperature air (typically 285°K). The HTPB was normally tested at higher air flow rates (typically 0.15-0.25 kg/sec). This fuel requires less inlet area change for flame stabilization but generally requires higher temperature air (>400°K) to sustain ignition.

It was not clear from the data whether the higher performance of PMM and the insensitivity of its performance to equivalence ratio in non-bypass operation was due primarily to the lower air flow rates used, or to differences in the fuel vapor compositions. It is known that PMM vaporizes primarily into a monomer whereas HTPB produces molecules with a wide range of molecular weights. Limited tests were conducted at low flow rates using HTPB and the combustion efficiency was found to significantly increase and to be insensitive to equivalence ratio. This limited data indicated that the increased mixing that occurs in turbulent flow for lower Reynolds numbers may have been the explanation for the increased performance of the PMM fuel. However, additional data are required for validation.

In this investigation tests were conducted to help clarify the effects of air flow rate (vs. fuel composition) and combustion pressure oscillations on combustion efficiency. PMM fuel grains were tested in a non-bypass mode with nominal (0.09 kg/sec) and high (0.15 kg/sec) air

flow rates. Fuel grain length was varied, at fixed air flow rate, to yield the desired variations in equivalence ratio. PMM grains were also tested in the bypass configuration. Sonically choked and unchoked air inlets were used to provide stable and unstable combustion, respectively, to determine the effects of the pressure oscillations on combustion efficiency.

To facilitate future investigations the SFRJ test apparatus was moved to a new facility. This move made available a greater volume of compressed air at higher pressures than previously available. Also incorporated into the new SFRJ test facility was a vitiated air heater, allowing higher inlet air temperatures (to 830°K) to be obtained when desired.

II. DESCRIPTION OF APPARATUS

A. RAMJET MOTOR

The ramjet motor assembly used in the experiments was that used previously at NPS [Refs. 1 and 2] with little modification (Figure 1). The primary parts of the motor are the aft mixing chamber, the fuel grain, and the air inlet section.

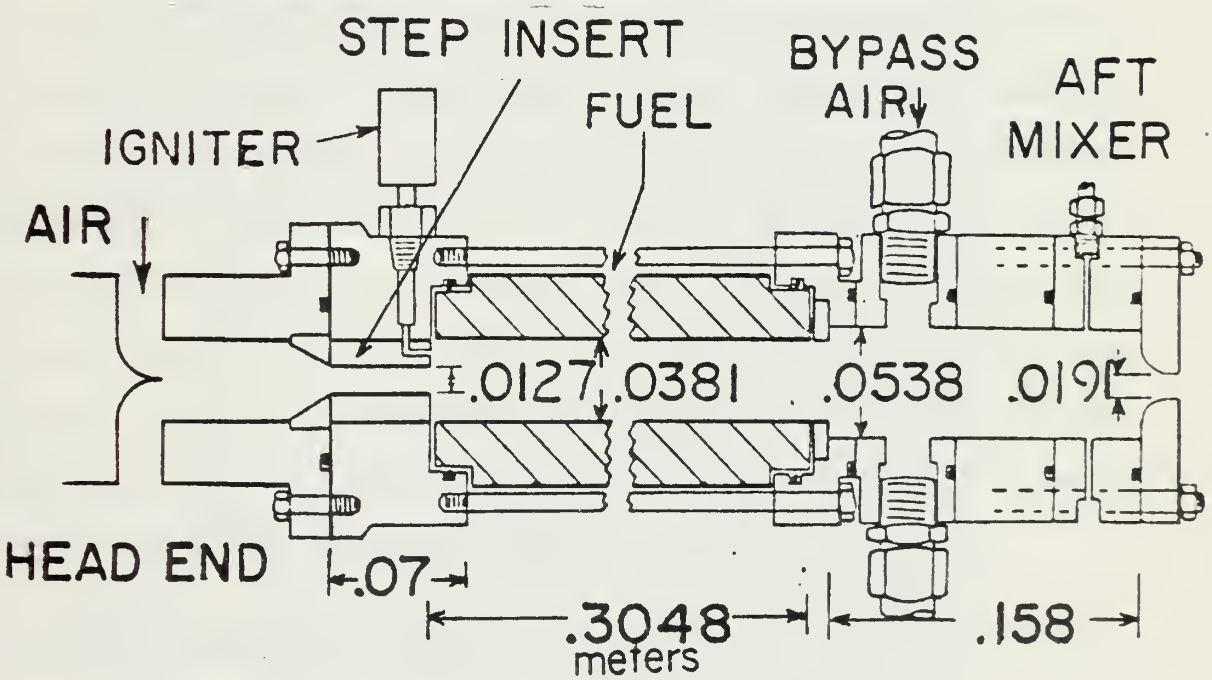

Figure 1. Schematic of Solid Fuel Ramjet Assembly

Primary air-flow is introduced into the head-end of the fuel grain from the air inlet section. This section also contains inlets for the ignition fuel (C_2H_4) and the igniter torch (C_2H_4/O_2) which are used to initiate combustion within the fuel grain. Also at the inlet head-end is a pressure tap which allows measurement of the inlet pressure.

A step insert (sudden-expansion) section allows variations in the air inlet diameter as needed.

The mid-section of the motor is a cylindrically perforated fuel grain. A grain is held securely in place by being recessed slightly into the head-end and aft mixing chamber sections and these two sections are tightly pulled together by three threaded rods and nuts.

In the aft mixing chamber, bypass air can be introduced at various axial locations and at various mass flow rates and/or inlet momentum. For non-bypass experiments the ports are plugged. At the aft end of the mixing chamber is the ramjet nozzle. A converging nozzle with a diameter of 1.91 cm was used for all PMM firings. An orifice is used at the aft end of the fuel grain to maintain a fixed area ratio between the fuel port and the aft mixing chamber during combustion. Also in the aft mixing chamber is a pressure tap which allows measurement of chamber pressure. The entire SFRJ motor assembly is shown in Figure 2.

B. AIR SUPPLY AND CONTROL SYSTEM

One of the primary reasons for moving the SFRJ testing to the new facility was the limited compressed air supply at the old facility, 10.34×10^5 N/m^2. The new facility has an air storage volume of 7.93 m^3

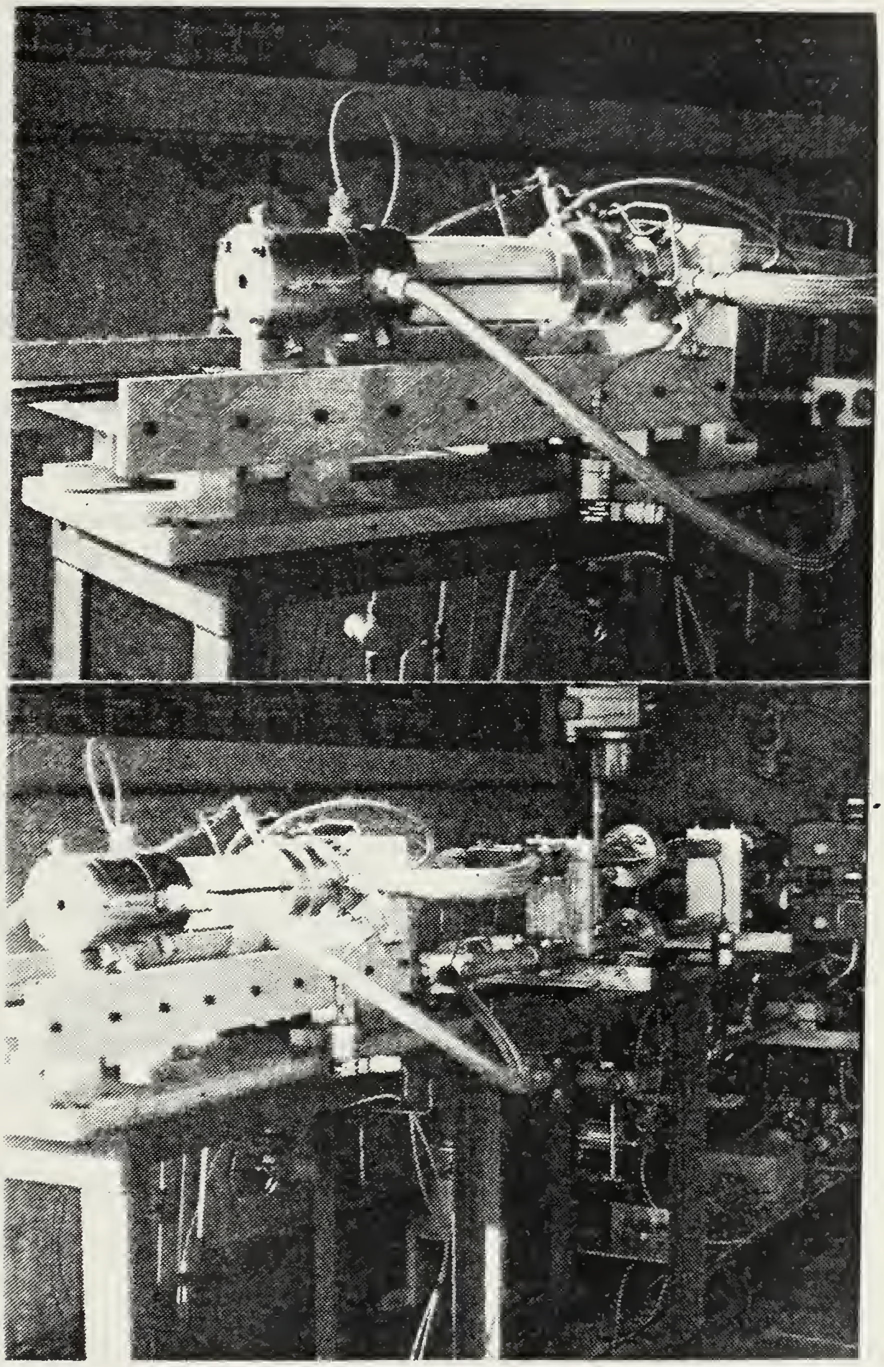

Figure 2. Photographs of Solid Fuel Ramjet Assembly

and stores air at pressures to 193. X 10^5 N/m^2. A schematic of the air supply system is shown in Figure 3.

Two remotely operated gate valves, one in the primary air line and one in the secondary air line, can be used to vary flow rates to the motor. When required, air flow can be vented to the atmosphere instead of through the motor by use of two pneumatically operated ball valves. Flow rate was measured using sonically choked flow nozzles.

C. DATA ACQUISITION SYSTEM

Pressure transducers and thermocouples are located in the system to measure flow nozzle pressures and temperatures, motor head-end and bypass pressures and temperatures and combustion chamber pressure. All pressures were recorded on a Honeywell 1508 Visicorder.

A five hertz signal from a frequency generator was used to provide an accurate time reference on the Visicorder.

Data obtained from the Visicorder, together with the weight loss of the grain, were used to determine air flow rates, fuel-to-air ratios, and average fuel regression rates.

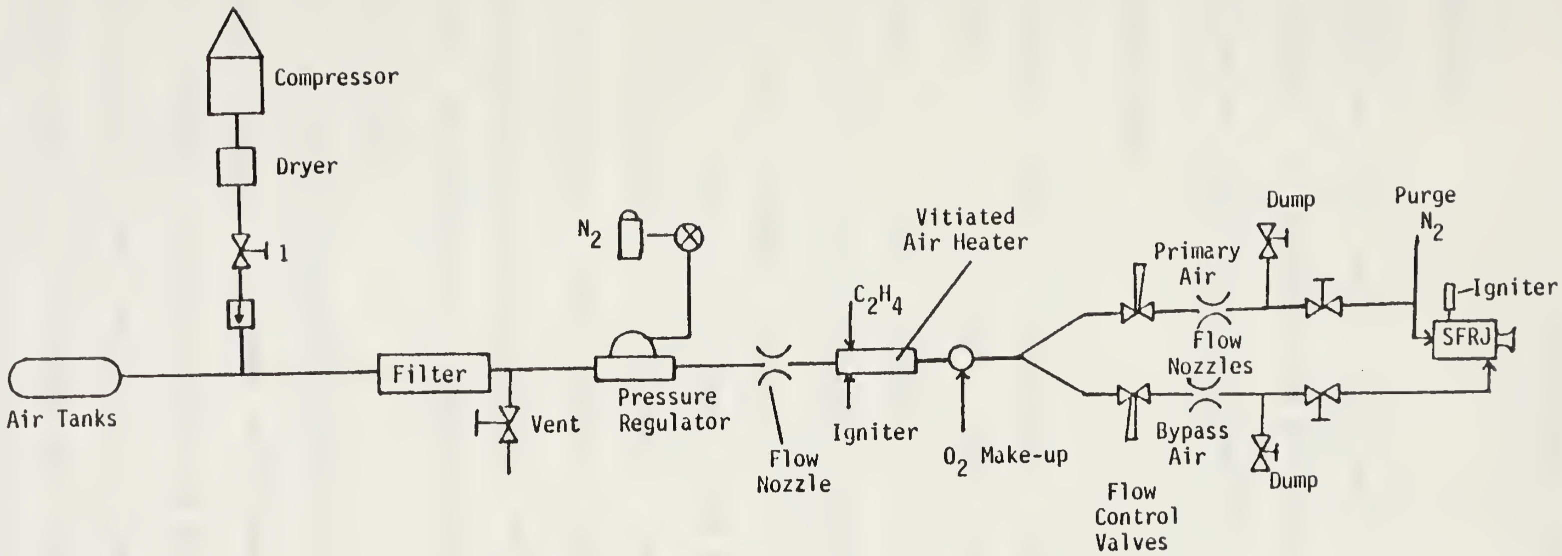

Figure 3. Schematic of Air Supply System

III. EXPERIMENTAL PROCEDURES

A. CALIBRATIONS

Each day the SFRJ was to be fired or when a different range of pressure readings was desired the pressure transducers were calibrated over the expected ranges of pressures with aid of a dead weight tester.

B. DATA EXTRACTION

The Honeywell 1508 Visicorder was used to record all pressures during a given run. A five hertz signal was recorded across the bottom of each trace as a time reference. The burn time of each run was obtained from the aft mixing chamber pressure trace. A typical run was 45 seconds long for bypass runs and nominal air flow rate (0.09 kg/sec) non-bypass runs. High air flow rate (0.15 kg/sec), non-bypass runs were burned for approximately 30 seconds. The burn time was controlled manually by the operator from a control panel.

Pressures that remained typically constant through a run (pressures upstream from the SFRJ motor) could be readily determined directly from the calibration data.

Chamber and motor head-end pressures varied over the duration of a run. Average pressure was then determined using a compensating polar planimeter to measure the area under the pressure-time trace. This area was then divided by the length of the base of the trace to yield an average trace height. This height was then matched against the corresponding pressure calibration to obtain the average pressure.

C. REACTING FLOW EXPERIMENTS

Following assembly of the motor and calibrations, compressed air was allowed to pass through the supply lines in order to obtain the air temperature. With this temperature and the known throat diameter of the sonic flow nozzle, the required nozzle upstream pressure was determined for the desired air mass flow rate from:

$$\dot{m} = K\, C_d\, P_a \left(\frac{d^2}{\sqrt{T_a}} \right) \tag{1}$$

where

C_d = nozzle discharge coefficient (0.97)

P_a = nozzle upstream pressure

d = nozzle throat diameter

T_a = nozzle upstream air temperature

K = constant (a function of γ and R)

The ignition sequence was started by setting the desired air-flow rate and then activating the ignition switch. The ignition switch activated both the ignition torch and the upstream injection of ethylene. The ignition time was typically two to three seconds to assure fuel grain flame stability. A run would be terminated by shutting off the air flow and purging the fuel grain with nitrogen.

After a run the fuel grain would be removed and weighed. This weight was then compared to the pre-run weight to determine the fuel weight loss during the run. The fuel weight loss was then divided by the run time to determine mass flow rate of the fuel.

The mass flow rate of air was determined from equation (1) using the Visicorder values of pressure obtained during the run and the feed air temperature recorded during the middle of the run. Fuel-air ratio and equivalence ratio could then be readily calculated. The theoretical adiabatic combustion temperature T_{th} was then generated as a function of fuel-to-air ratio and combustion pressure using the NWC PEPCODE computer program (run on the IBM-3033 system computer at the Naval Postgraduate School).

To find the combustor efficiency the experimental combustion stagnation temperature T_{ex} must first be determined. For one-dimensional flow of a gas through a sonically choked nozzle:

$$T_{ex} = \frac{g_c \gamma}{R} \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}} \left(\frac{C_d \overline{P_c} A^*}{\dot{m}_t}\right)^2 \qquad (2)$$

where

R = gas constant obtained from PEPCODE

γ = ratio of specific heats obtained from PEPCODE

A^* = nozzle throat area

$\overline{P_c}$ = average chamber pressure

$\dot{m}_t$ = total mass flow rate of air and fuel

C_d = nozzle discharge coefficient (.97)

Once T_{ex} and T_{th} were determined the combustion efficiency η was calculated using:

$$\eta = \frac{T_{ex} - T_a}{T_{th} - T_a} \tag{3}$$

where T_a was the feed air temperature recorded mid-way through the run.

The average fuel regression rate was also determined based on the change from the initial to final average diameter of the fuel grain port. The initial average diameter was measured prior to the run. The final average diameter was determined based on weight loss and fuel length by using:

$$D_{fav} = \sqrt{\frac{4(\Delta w_f)}{\pi \rho L} + Di_{av}^{\,2}} \tag{4}$$

where

Δw = weight change

L = length of fuel grain

ρ = density of PMM

Di_{av} = average initial port diameter of PMM grain

The average fuel regression rate was then computed using:

$$\dot{r}_{av} = \frac{D_{fav} - Di_{av}}{2\, t_b} \tag{5}$$

where t_b = burn time.

IV. RESULTS AND DISCUSSION

A. INTRODUCTION

In this chapter the results of each of the four areas of interest are discussed. A total of 15 experiments were conducted. The results of these experiments are contained in Table 1. Figure 4 is a graph of combustion efficiency vs. mixture ratio for all runs.

B. NON-BYPASS OPERATION WITH NOMINAL (0.09/kg/sec) AIR MASS FLOW RATE

In this area of the experimental investigation PMM grain length was varied to give a relatively broad span of equivalence ratios (Table 2, Figure 4) with fixed air mass flow rate. The data indicated that combustion efficiency varied somewhat with equivalence ratio, with a maximum near an equivalence ratio of 0.75. However, the variation was not large. This variation is typical of data for HTPB fuels [Ref. 2]. Previous data [Ref. 2] have indicated less dependence of combustion efficiency on equivalence ratio for PMM. It was also noted that the efficiencies were lower than obtained in Ref. 2. This was most likely due to the much lower air inlet temperatures used in the present investigation. The temperature of the inlet air was approximately 45°K colder than in earlier runs. The lowering of inlet air temperature is known to have a negative effect on the burning efficiency of most SFRJ fuels. The lowering of the combustion efficiency may have also aggravated the noted effect of equivalence ratio on efficiency, not noticed at higher air inlet temperatures.

Table 1. Test Results

EXPERIMENT NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
CONFIGURATION *	NBP-N	NBP-N	NBP-H	NBP-H	NBP-H	NBP-N	NBP-N	NBP-H	BP-C	BP-C	BP-C	BP-UC	BP-UC	BP-UC	BP-UC
L (cm)	28.36	40.56	48.7	36.5	43.3	32.3	44.6	38.0	54.3	30.4	43.2	50.7	30.5	30.5	45.7
Δw_f (gm)	323	499	571	391	822	469	657	754	464	254	390	601	395	334	262
$\dot{m}_p$ (g/sec)	7.1	10.6	19.0	13.2	18.3	8.6	11.9	14.9	9.0	5.0	7.8	10.6	6.5	6.5	9.8
T_b (sec)	45.4	46.8	30.0	29.6	45.0	54.4	55.0	50.6	51.6	51.0	50.0	56.8	60.4	51.7	26.8
$\dot{m}_a$ (g/sec)	103.5	99.1	170.2	171.4	166.5	92.6	94.4	154.8	91.1	91.3	92.3	91.7	91.8	91.1	92.6
$\dot{m}_t$ (g/sec)	110.6	109.8	189.2	184.6	184.8	101.2	106.3	169.7	100.1	96.3	100.1	102.3	98.3	97.6	102.4
f/a	.0735	.1075	.1118	.0770	.1097	.0931	.1266	.0962	.0987	.0546	.0845	.1154	.0712	.0660	.1055
ϕ	.6126	.8958	.9317	.6420	.9142	.7759	1.055	.802	.823	.4547	.7040	.9619	.5900	.5497	.8790
$\bar{P}_c$ (N/M²) X 10³	363.4	430.2	728.7	669.5	742.6	387.5	408.2	658.4	397.8	318.5	381.3	382.6	368.9	356.5	370.2
T_{ex} (K)	1477	1815	1752	1569	1912	1740	1790	1787	1872	1319	1730	1653	1683	1615	1547
T_{th} (K)	1719	2177	2234	1772	2200	2006	2301	2067	2096	1437	1905	2272	1708	1625	2176
d_f (cm)	5.27	5.27	5.21	5.11	5.92	5.50	5.52	5.99	4.87	4.85	4.93	5.23	5.34	5.13	5.77
$\dot{r}$ (cm/sec)	.0155	.0155	.0233	.0218	.0234	.0155	.0155	.0216	.0102	.0102	.0112	.0124	.0126	.0119	.0105
η (%)	85.3	81.3	75.8	86.7	86.0	84.9	77.1	84.5	87.9	90.0	89.3	70.0	98.0	99.1	67.0

* NBP-N - Non-bypass nominal flow rate
NBP-H - Non-bypass high flow rate.
BP-C - Bypass, Choked
BP-UC - Bypass, Unchoked

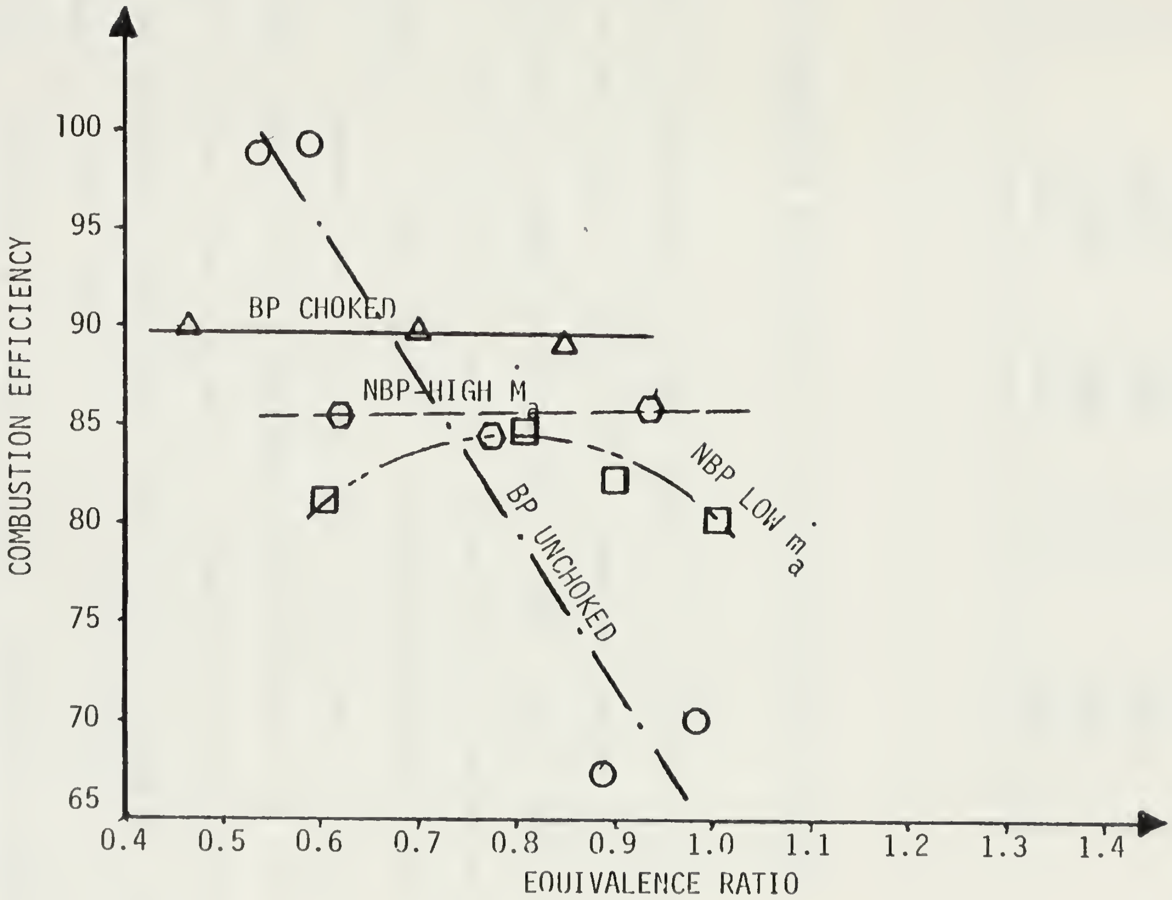

Figure 4. Efficiency vs. Equivalence Ratio, All Runs

Table 2. Performance Summary for Non-Bypass, Nominal Flow Rate

Test No.	L (cm)	ϕ	η	$\dot{r}$ (cm/sec)
1	28.36	.6126	85.3	.0155
6	32.30	.7759	84.9	.0155
2	40.56	.8958	81.3	.0155
7	44.6	1.055	77.1	.0155

C. NON-BYPASS OPERATION WITH HIGH (0.15 kg/sec) AIR MASS FLOW RATE

The higher air mass flow rate was chosen to be nearly the same as used in earlier tests [Ref. 2] with HTPB in order to examine the effects of turbulent mixing on combustion efficiency. Table 3 and Figure 4 show the combustion efficiencies for runs 4, 5, and 8, all non-bypass with high (0.15 kg/sec) air mass flow rate. Varying equivalence ratio had little effect on combustion efficiency and the values of combustion efficiency were similar to the maximum value obtained from the non-bypass, nominal air mass flow rate tests. Increasing air mass flow rate (and, therefore decreasing turbulent mixing) did not appear to effect the performance of PMM. This is in contrast to results for HTPB [Ref. 2], where increased air mass flow rate decreased combustion efficiency. These limited results do imply that fuel composition (more

Table 3. Performance Summary for Non-Bypass, High Flow Rate

Test No.	L (cm)	ϕ	η	$\dot{r}$ (cm/sec)
4	36.5	.6420	86.7	.0218
8	38.0	.802	84.5	.0216
5	43.3	.9142	86.0	.0234
3*	48.7	.9317	75.8	.0233

* Apparently bad data (Viscorder recording failure)

specifically, fuel vapor composition) does have an effect on the obtainable combustion efficiency. It should be noted that overall combustion efficiency of the SFRJ depends both upon the diffusion limited combustion within the port of the fuel grain and on the combustion process within the aft mixing chamber. The latter may be mixing or kinetics limited (or involve both), depending upon the dependence of reaction rate on temperature.

D. BYPASS OPERATION, SONICALLY CHOKED AIR INLETS

In these experiments the air inlets at the head-end and the bypass dumps were sonically choked to isolate the combustion process from the air feed system. The test results did indicate that stable combustion was always obtained. Table 4 and Figure 4 show the results for runs 9, 10, and 11. These runs were made with a nominal mass flow rate of air

Table 4. Performance Summary for Bypass, Choked

Test No.	L (cm)	ϕ	η	$\dot{r}$ (cm/sec)
10	30.4	.4547	90.0	.0102
11	43.2	.7040	89.5	.0112
9	54.3	.8230	87.9	.0102

(0.09 kg/sec). Variations in the equivalence ratio had little effect on the combustion efficiency.

The results show an increase of approximately 5% in efficiency over that obtained in non-bypass runs of the same mass flow rates. This was an unexpected result when compared to earlier tests [Ref. 2]. It has been suggested that the bypass air has a tendency to quench the combustion process occurring in the aft mixing chamber (using PMM), resulting in a lower overall combustion efficiency than that experienced with non-bypass. The much lower air inlet temperature used in the present investigation may again have caused this difference in observed results. The combustion efficiency within the port of the fuel grain (vs. the total combustor) was apparently reduced significantly with the non-bypass, cold inlet air conditions.

E. BYPASS OPERATION, SONICALLY UNCHOKED AIR INLETS

The air mass flow rate (0.09. kg/sec) was divided 50/50 for these bypass tests. Table 5 and Figure 4 show the results for runs 12 through 15. The head-end inlets and bypass dumps were unchoked, to allow interactions to occur between the air feed system and the combustion process. The test results (pressure trace and audible noise) did indicate that combustion pressure oscillations occurred in all of these tests, with a frequency of 120 Hertz and a peak-to-peak pressure variation greater than 10% of the average chamber pressure.

Table 5. Performance Summary for Bypass, Unchoked

Test No.	L (cm)	ϕ	η	$\dot{r}$ (cm/sec)
13	30.5	.5900	98.0	.0126
14	30.5	.5497	99.8	.0119
15	45.7	.8790	67.0	.0105
12	50.7	.9619	70.0	.0124

The unstable runs resulted in very high efficiencies with low equivalence ratios and very low combustion efficiencies at high equivalence ratios. The data also indicated that the instabilities resulted in an increased regression rate of approximately 10% above that obtained when

a stable condition was present. This increased regression rate was in agreement with the results reported in Ref. 2.

These results (sections D and E) have helped to clarify some of the earlier reported [Ref. 2] results for effects of combustion pressure oscillations on the combustion behavior. However, the complexity of the interactions between the pressure oscillations and the combustion within the fuel grain port and the aft mixing chamber has been further emphasized. The pressure oscillations appear to always increase fuel pyrolysis rates but have significantly different effects on combustion efficiency depending upon the equivalence ratio. When the equivalence ratio was near 1.0 within the fuel port (lean overall equivalence ratio) the combustor process was enhanced and when the equivalence ratio was greater than 1.0 in the fuel port (near an equivalence ratio of 1.0 overall) the combustor process was degraded.

V. CONCLUSIONS AND RECOMMENDATIONS

The limited experimental data of this investigation have indicated that fuel vapor composition within the SFRJ combustor may have a significant effect on the obtainable combustion efficiency and upon the dependence of combustion efficiency upon equivalence ratio and air mass flow rate. Combustor pressure oscillations in bypass operation were found to increase fuel regression rates and to increase or decrease combustion efficiency depending upon the equivalence ratio.

The combustor efficiency of PMM in the non-bypass SFRJ geometry was significantly decreased when lower air inlet temperatures were used. Further tests should be conducted to increase the data base and tests using higher inlet air temperatures in the new test facility should be made for direct comparison with the data recorded in Ref. 2.

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Thesis
B3527 Begley
c.1 An experimental
investigation of the
combustion behavior
of solid fuel ramjets.